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Drying characteristics and quality of rough rice under infrared radiation heating

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Abstract. *Infrared (IR) radiation heating could provide high heating rate and rapid moisture removal for rough rice drying. The objective of this research was to investigate the effect of drying bed thickness on drying characteristics and quality of rough rice under IR heating. The samples of freshly harvested medium grain rice (M202 variety) with 20.5 % and 23.8% (wb) moisture contents were used for this study. They were dried with two different radiation intensities, 4685 and 5348 W/m^2, for six exposure times, 15, 30, 40, 60, 90 and 120 s, for each drying bed thickness. The tested three drying bed thicknesses were single layer, 5 mm and 10 mm. After IR drying, the samples were tempered for 4 hours followed by slow cooling. The drying rate, moisture removal and temperature of rice during drying were measured and calculated. The rice temperatures after the IR heating were in the range of 35.9 to 71.4 ºC. The heating and drying rates decreased with the increase of bed thickness. A significant amount of moisture was removed during slow cooling after tempering, without additional energy input. The quality of milled rice, including total rice yield, head rice yield, and degree of milling of the dried rice was evaluated. It was concluded that a high heating rate, fast drying and good rice quality could be achieved by heating rough rice to about 60 ºC followed by tempering and slow cooling with a bed thickness up to 10 mm.*

Keywords. Infrared, Rough rice, Drying, Bed thickness, Quality.

Introduction

Rough rice drying is a critical post harvest handling process and has a direct effect on rice quality, subsequent handling processes and commercial value of rice crop. Rough rice is normally harvested at a moisture content higher than the required moisture of 12% to 14% (wet basis) for safe storage. Rough rice is typically dried using heated air, which is a slow process because only relatively low air temperatures can be used to avoid reducing rice milling quality.

Rough rice drying occurs primarily through convection. The heated air warms the outer layer of the rice kernel first and causes the moisture to evaporate from the kernel surface into the drying air. As the moisture is removed from the outer layers of the grain, moisture and temperature gradients are established within the kernel. These gradients cause stresses in the grain, causing the rice kernel to break after drying (Ban, 1971; Kunze and Choudhury, 1972; Kunze, 1979). Therefore, to minimize moisture gradients the typical drying process uses low heated air temperature up to 54ºC and multiple drying passes by removing relatively small amount of moisture (2% - 3%) in each pass (Kunze and Calderwood, 1985).

With the increase in rice production due to higher yielding varieties and more rapid harvesting and transport capabilities, it is important to find a method to dry rice with high energy efficiency and quality. Infrared drying has been investigated as a potential method for obtaining high quality dried foodstuffs, including fruits, vegetables and grains (Abe & Afzal, 1997; Afzal & Abe, 1998, 2000; Hebbar & Rostagi, 2001; Zhu, Zou, Chu, & Li, 2002). IR radiation drying is fundamentally different from convection drying where the material is dried directly by absorption of IR energy rather than transfer of heat from the air (Bal, Wratten, Chesnen, & Faulkner, 1970). IR energy is transferred from the heating element to the product surface without heating surrounding air. The radiation impinges the exposed material and penetrates it and is converted to sensible heat (Ginzburg, 1969). The penetration could provide more uniform heating in rice kernel and may reduce the moisture gradient during heating and drying. Also, since IR does not heat up the medium, the temperature of rice kernel is not limited by the wet bulb temperature of surround air and high temperature of rice kernel can be achieved in a short time.

Infrared heating offers many advantages over conventional drying such as: high drying rate, decreased drying time, high energy efficiency, high quality finished products, uniform temperature in the product during drying process, and a reduced necessity for air flow across the product (Sharma, Verma, & Pathare, 2005).

The earliest research using IR for drying rough rice was reported in early 1960s (Schroeder and Rosberg, 1960; Schroeder, 1960 and 1961; Hall, 1962; Faulker and Wratten, 1966 and 1970). High drying rate of rice was achieved by spreading the rice in a single layer. When IR was used to preheat the rough rice to 60°C followed by 49°C heated air drying for 2-3 min, approximately 2% MC was removed during each drying pass. It has also been reported that it took only 7 minutes to reduce the moisture content from 20% to 14.8% (db) using near infrared heating compared to 30 minutes for hot air drying (Rao, 1983). Recently, most of research used medium and far infrared with wavelength of 2-100μm for drying agricultural products (Arinze et al., 1987; Nindo el al., 1995). Bekki (1991) found that the maximum absorption of infrared radiation by medium grain rough rice occurred at a wavelength of 2.9 μm.

Due to limited penetration capability of IR, it is important to know the maximum rice drying bed thickness for achieving high heating and drying rates and high rice quality. And also, since the infrared can be used to heat rough rice with single or thin layer quickly to a relatively high temperature; it is possible to use the sensible heat from the heated rice to remove more moisture during cooling, which could make the overall IR rough rice drying more energy efficient. However, no reported research has focused on this aspect. The objectives of this research were (1) determine the effect of drying bed thickness on heating and drying rates of rice under different infrared heating times, (2) study the characteristics of moisture removal with tempering and slow air cooling, (3) investigate the milling quality of rice dried with infrared under selected conditions and (4) determine optimum operational parameters of infrared dryer.

Materials and methods

Infrared Drying Device

A laboratory scale infrared dryer was developed in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The infrared dryer comprised of two components, infrared emitter and drying bed. The catalytic emitter provided by Catalytic Industrial Group (Independence, Kansas) was used as infrared radiation source. The emitter generated IR by catalyzing natural gas to produce heat along with small amounts of water vapor and carbon dioxide as by-products. The dimension of the emitter was 30 x 60 cm with surface temperature at about 730 ºC with corresponding peak wavelength 3.6µm assuming the emitter as a blackbody. The heater surface temperature was measured by type-T thermocouples embedded at eight different locations on the heater surface. An aluminum box with dimension of 65 cm (length) x 37 cm (width) x 45 cm (height) was installed around the emitter as wave guide to achieve the uniform intensity at the rice bed surface. The dimension of the drying bed was 90 cm (length) x 35 cm (width) x 7 cm (depth) made from an aluminum sheet of 3 mm thickness to minimize energy loss. Two type-T thermocouples were embedded on the bed surface to measure the bed temperature.

The rice bed was set at 5 and 10 cm below the bottom edge of the wave guide with corresponding average IR intensities of 4685, and 5348 W/m2 at the rice bed surface. The radiation intensity was measured by using Ophir FL205A Thermal Excimer Absorber Head (Ophir,Washington, MA).

Rough Rice and Control Samples

Freshly harvested medium grain rice, variety M202, obtained from Farmer's Rice Cooperative (West Sacramento, CA), was used for conducting the IR drying tests. The moisture content of rough rice was 23.8±0.3% (high MC) at the harvest. The rice sample with the high MC was equally divided into two portions. In order to obtain one rough rice sample with low initial MC, the other portion of the sample was slowly dried to 20.5±0.2% (low MC) with room temperature from 18°C to 20°C on the floor in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. The thickness of rice bed on the floor was less than 5 cm. During the slowing drying the rice was mixed frequently to ensure uniform drying. It took about 45 hours to reach the 20.5% MC. Then the rice samples with both 20.5% and 23.8 % MC were kept in polyethylene bags and sealed to ensure no moisture loss before they were used for the IR drying tests. The rice samples were further divided into 500 g samples with a sample divider (Boerne-sampler, seed trade, reporting bureau, Chicago, ILL.) at the test time. Control samples were prepared by drying the samples with original moisture contents of 20.5 and 23.8 % using ambient air at 0.1 m/s to final moisture content of 13 ± 0.2 %. All reported moisture contents are on wet weight basis and determined by the air oven method (130°C for 24 h) (ASAE, 1995).

Experimental Design

Rice samples were dried under the following conditions

Table 1. Experimental design

Initial moisture content (% wb)	Drying bed thickness	Heating time (s)			
	Single – layer	15	40	60	90
20.5	5 mm	30	60	90	120
	10 mm	30	60	90	120
	Single – layer	15	40	60	90
23.8	5 mm	30	60	90	120
	10 mm	30	60	90	120

Infrared Radiation Drying Procedures

The rice samples with the two initial moisture contents were heated for six heating time durations (15, 30, 40, 60, 90 and120 s) under IR radiation intensity of 4685, and 5348 W/m^2. All tests were replicated three times at each condition. For the drying test, a 500 g rice sample was placed on the drying bed as single layer (2 mm), 5 mm, and 10 mm with loading rate of 2.5, 4.5, and 6.5 kg /m^2, respectively. Single-layer drying was conducted by spreading the rice samples as a single layer on the drying bed. The thickness of single layer was determined by measuring the thickness of rice kernels with initial moisture contents of 20.5 % and 23.8 % (200 kernels). The thickness average was 2 ± 0.01 mm. The initial drying bed temperature was 35 ºC.

To determine the drying characteristics under different heating conditions, the rice temperature and moisture loss were measured at the end of each heating period. The rice temperature was measured by thermometers (Solomat MPM 500, UK) and (Visor Handspring Inc., U.S.A.). The rice sample weight was measured using a gram balance with two-decimal place accuracy before and after heating. The weight loss during infrared heating and the original moisture content were used to calculate the moisture removal (the difference between the original and final moisture contents) expressed as percentage points, wet basis moisture.

Tempering and Slow Cooling Procedures

In order to study the effects of tempering on moisture loss during cooling, and milling quality, both tempering and slow cooling treatments were conducted. The tempering was conducted by keeping rice samples in closed containers placed in an incubator with a temperature as same as the heated rice for 4 h immediately following the heating. After the tempering treatment, rice samples were cooled using slow cooling at room temperature of 22°C to 24°C as a thin layer (about 1 cm thick).The thin layer of rice was placed on a laboratory bench for about 35 min. The temperatures of rice samples were close to ambient temperature at the end of cooling. The weight changes caused by the cooling treatment were recorded at the end of cooling and used to calculate the moisture removal based on the moisture contents after the corresponding IR heating treatments. The cooled samples were stored in polyethylene bags for one day before they were further dried to 13.5±0.2% MC using room air. The samples were stored in Ziplock bags at room temperature for about one month before milling.

Milling Quality Evaluation

The most important rice milling quality indicators are total rice yield (TRY), head rice yield (HRY) and degree of milling. The rice 400 g samples were dehulled and milled by using Yamamoto Husker (FC-2K) and Yamamoto Rice Mill (VP-222N, Yamamoto Co. Ltd., Japan). They were milled three times to achieve the well milled rice as defined by the Federal Grain Inspection Service (USDA FGIS, 1994). For the first two times, the settings of Throughput and Whitening were 1 and 4, respectively. For the third time, the settings were 1 and 5. HRY was determined with Grainchecker (Foss North America, Eden Prairie, MN). The Whiteness Index (WI) was used to evaluate degree of milling of milled rice and determined with the Whiteness Tester, C-300, (Kett Electronic Laboratory, Tokyo, Japan). A higher index number indicates whiter milled rice.

Statistical Analysis

The Sigma Stat software (Version 2.0, Jandel corporation, San Rafael ,CA) was used to find a multiple linear regression model between independent and dependent variables. Data of the rice milling quality were statistically evaluated ($p < 0.05$) by Sigma state software using one way RM ANOVA and multiple comparisons to compare treatments for significant differences.

Results and Discussion

Effect of Heating Time, Radiation Intensity and Drying Bed Thickness on Rice Temperatures

The rice sample temperatures with different heating durations at different initial moisture contents, radiation intensities, and drying bed thicknesses are presented in tables 1 and 2.The rice temperature increased with increasing heating duration and radiation intensity under the same initial moisture content and drying bed thickness. For example, when the rice samples with initial moisture content of 20.6% were heated at drying bed thicknesses of single-layer, 5 mm and 10 mm and radiation intensity of 5348 W/m^2, the temperatures of rice were 61.8, 53.4 and 46.2 ºC for 60 s heating and 69.4, 60.2, and 53.4 ºC for 90 s heating, respectively. Similarly, the rice temperatures were 60.6, 50.6, and 46.0 ºC for 60 s heating and 67.5, 59.1 and 52.3 ºC for 90 s heating for rice samples with initial moisture content of 23.8% heated at drying bed thicknesses of single-layer, 5 mm and 10 mm, respectively.

The temperature of rice samples increases with the increase of the radiation intensity. For example, when the rice samples with initial moisture content of 20.5% were heated for 60 s the rice temperatures were 52.7, 48.3, and 39.7 ºC under radiation intensity of 4658 W/m^2 and 61.8, 53.4, and 46.2 ºC under radiation intensity of 5348 W/m^2 at drying bed thicknesses, single-layer, 5 mm, and 10 mm, respectively.

The heating rate decreased with increase of the drying bed thickness. However, the decrease in the heating rate was not proportional. For example, under radiation intensity of 5348 W/m^2 the temperatures of rice samples with initial moisture content of 20.6 % were 61.8, 60.2 and 61.2 ºC at heating time of 60, 90 and 120s at drying bed thicknesses of single- layer, 5 mm, and 10mm, respectively. It can be seen that doubled thickness (from 5 to 10mm) did not require doubled heating time to reach to the temperatures about 60-61ºC which means that high heating rate could be achieved during short time by increasing the drying bed thickness up to 10 mm.

Table 2. Rice temperatures under different heating time, drying bed thickness and initial moisture contents at radiation intensity of 5348 W/m^2.

Heating time (s)	Initial moisture content (20.5 %)			Initial moisture content (23.8 %)		
	Single-layer	5 mm	10 mm	Single-layer	5 mm	10 mm
15	42.6±0.6			42.4±0.3		
30		40.6±0.5	37.0±0.9		39.7±0.5	35.9±0.7
40	54.5±0.4			53.8±0.3		
60	61.8±0.8	53.4±0.4	46.2±0.6	60.6±0.6	50.6±0.7	46.0±0.9
90	69.4±0.9	60.2±0.6	53.4±1.0	67.5±0.6	59.1±0.7	52.3±1.0
120		71.4±0.8	61.2±0.9		70.5±0.7	60.3±0.5

Table 3. Rice temperatures under different heating time, drying bed thickness and initial moisture contents at radiation intensity of 4658 W/m^2.

Heating time (s)	Initial moisture content (20.5 %)			Initial moisture content (23.8 %)		
	Single-layer	5 mm	10 mm	Single-layer	5 mm	10 mm
40	48.8±0.6			47.7±0.9		
60	52.7±0.5	48.3±0.6	39.7±0.6	50.7±0.8	47.1±0.9	36.9±0.9
90	60.2±0.3	51.9±0.2	44.5±0.5	57.8±0.7	51.2±0.8	43.4±0.9
120		57.0±0.8	49.6±0.6		56.4±0.8	47.5±0.8

In general, the low MC rice samples had slightly higher temperatures than the high MC rice samples, especially, at 60, 90, and 120 s heating time, which could be due to less energy being used for heating the water and a lower evaporative cooling effect in the low MC rice than in the high MC rice with the constant radiation heat supply. The maximum difference in temperatures of the samples with different original MC under the same heating duration was only 2.8 ºC. In order to accurately predict the rice temperatures under various operating conditions, which is important in the design of drying systems a multiple linear regression model was obtained

Rice temperature (ºC) = - 18.196 + (0.262 * Ht) - (1.797 * DBT) + (0.0121*RI)

In the model, the operation parameters, heating time Ht (s), drying bed thickness DBT (mm) and radiation intensity RI (W/m^2) are independent variables. The model has r^2 = 0.93.The model can be used to predict the temperature change for the rice with known heating time, drying bed thickness, and radiation intensity under tested moisture range and bed temperature. The predicted and experimental rice temperatures of low and high MC rice samples at different heating durations and drying bed thicknesses are presented in Fig.1.

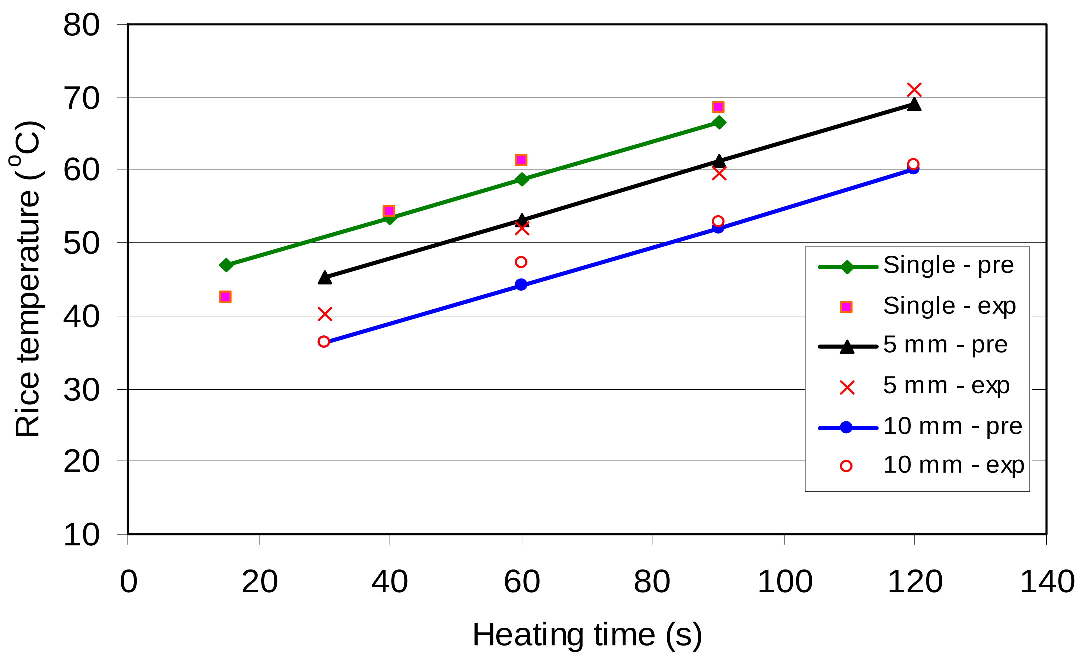
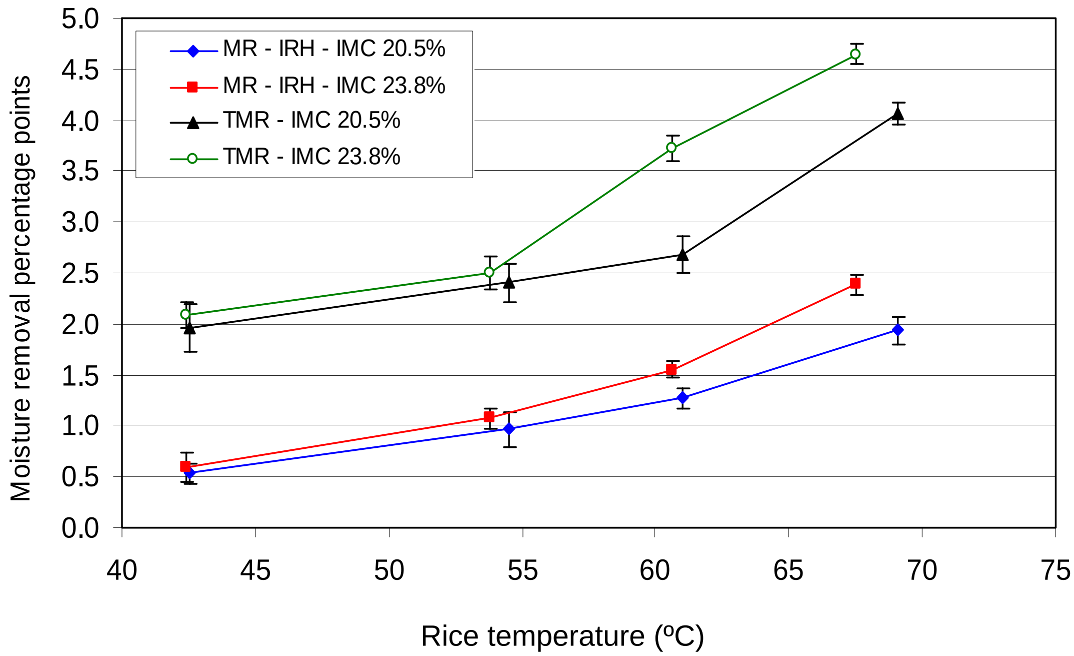


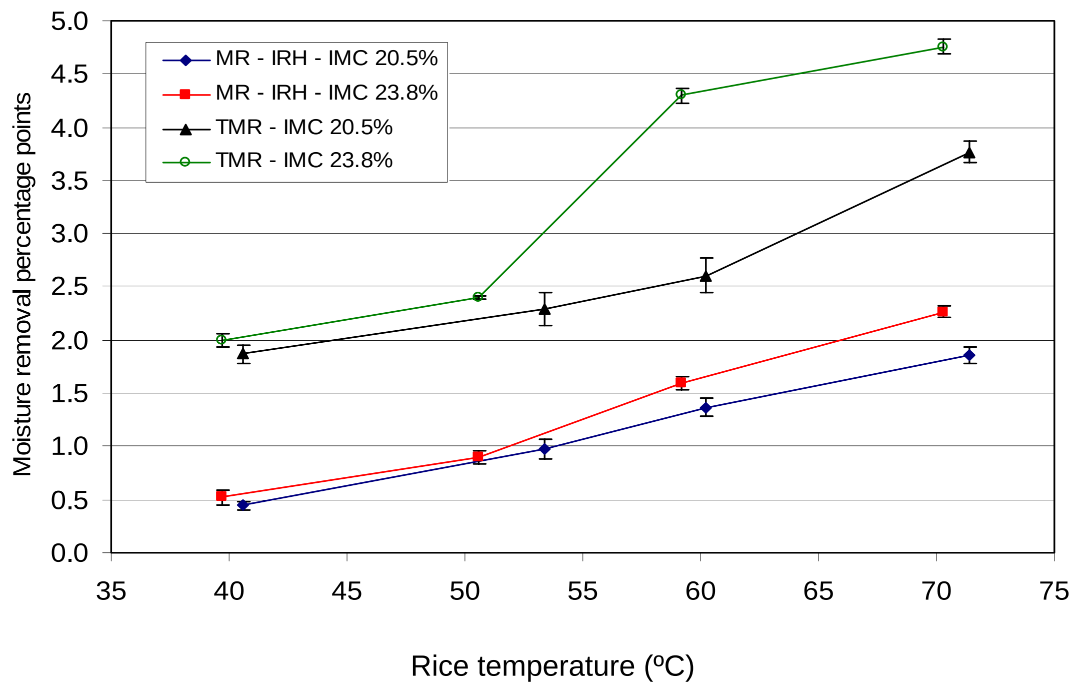
Figure 1. The predicted and experimental rice temperatures at different heating times and different drying bed thicknesses under radiation intensity of 5348 W/m^2

Moisture Removal under Different Drying Treatments

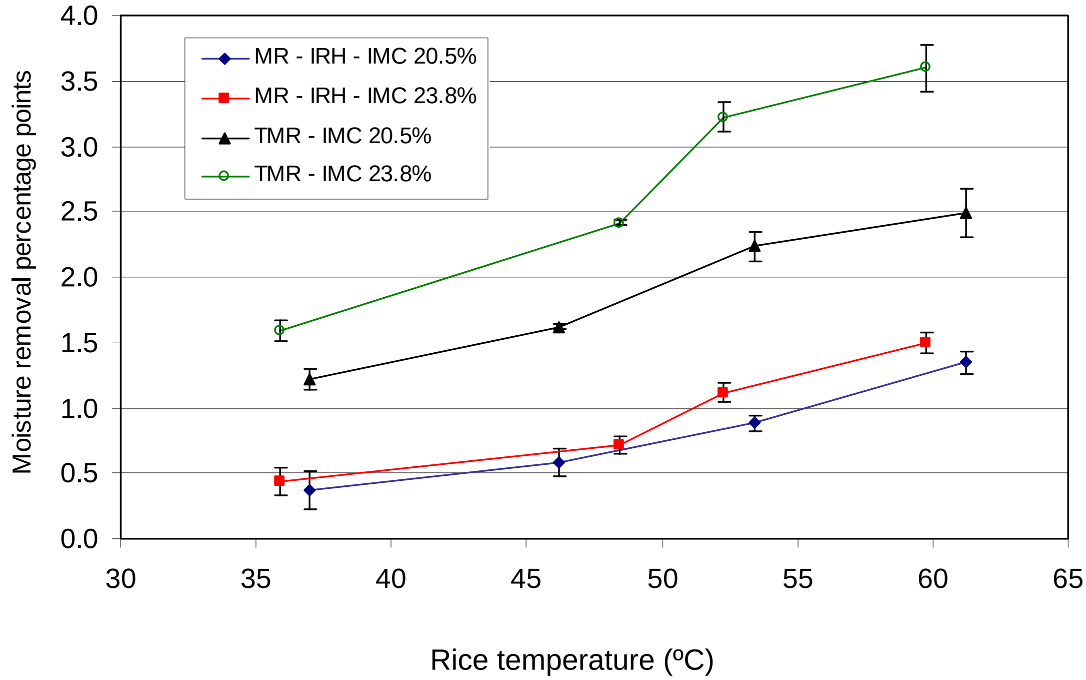
The moisture removal for rice samples with initial moisture of 20.5% and 23.8 % during infrared heating and after tempering treatment under different drying bed thicknesses and radiation intensities are shown in Figs.2 and 3.


MR - IRH - IMC 20.5%
MR - IRH - IMC 23.8%
TMR - IMC 20.5%
TMR - IMC 23.8%
Moisture removal percentage points
Rice temperature (ºC)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
40
45
50
55
60
65
70
75

(a)


MR - IRH - IMC 20.5%
MR - IRH - IMC 23.8%
TMR - IMC 20.5%
TMR - IMC 23.8%
Moisture removal percentage points
Rice temperature (ºC)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
35
40
45
50
55
60
65
70
75

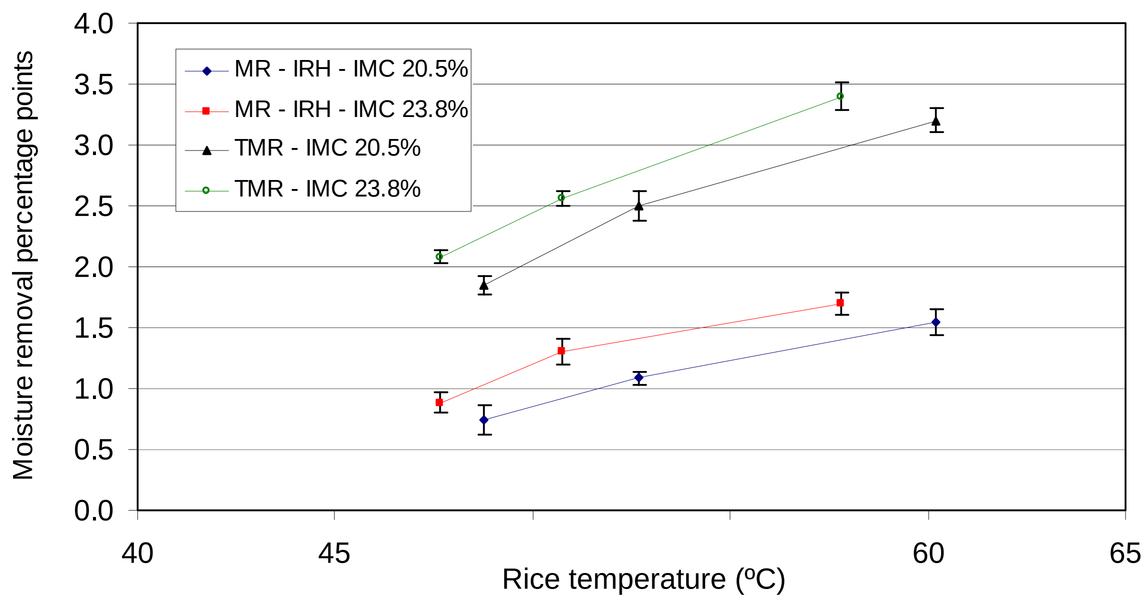
(b)



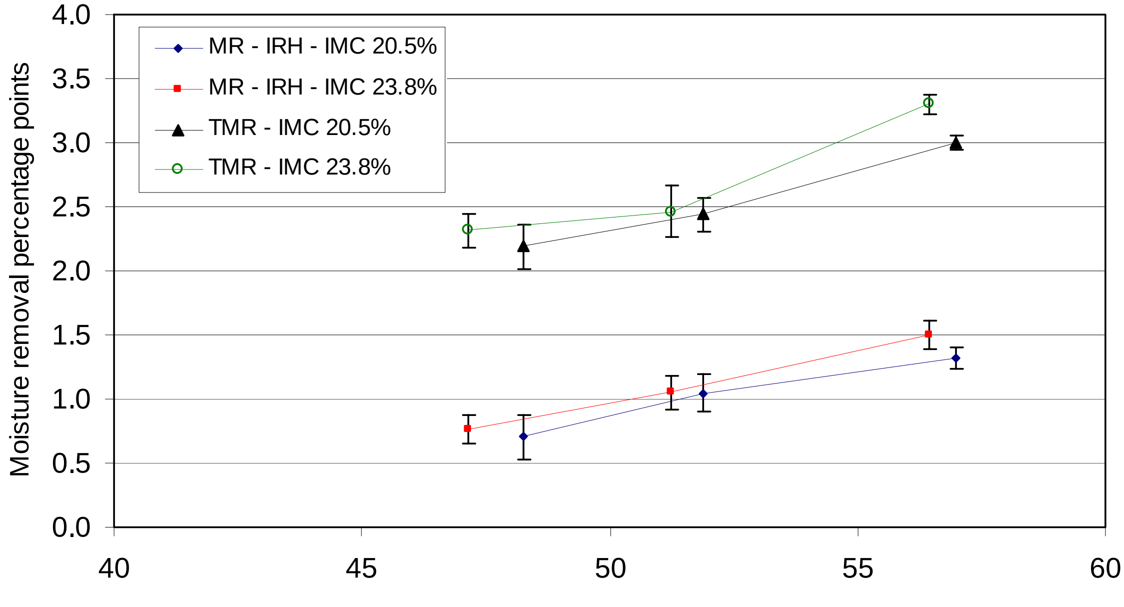
(c)

Figure 2. Moisture removal of rice with initial MC of 20.5 % and 23.8% during infrared heating and after tempering treatment with drying bed thicknesses of single-layer (a), 5 mm (b), and 10 mm (c) under radiation intensity of 5348 W/m^2

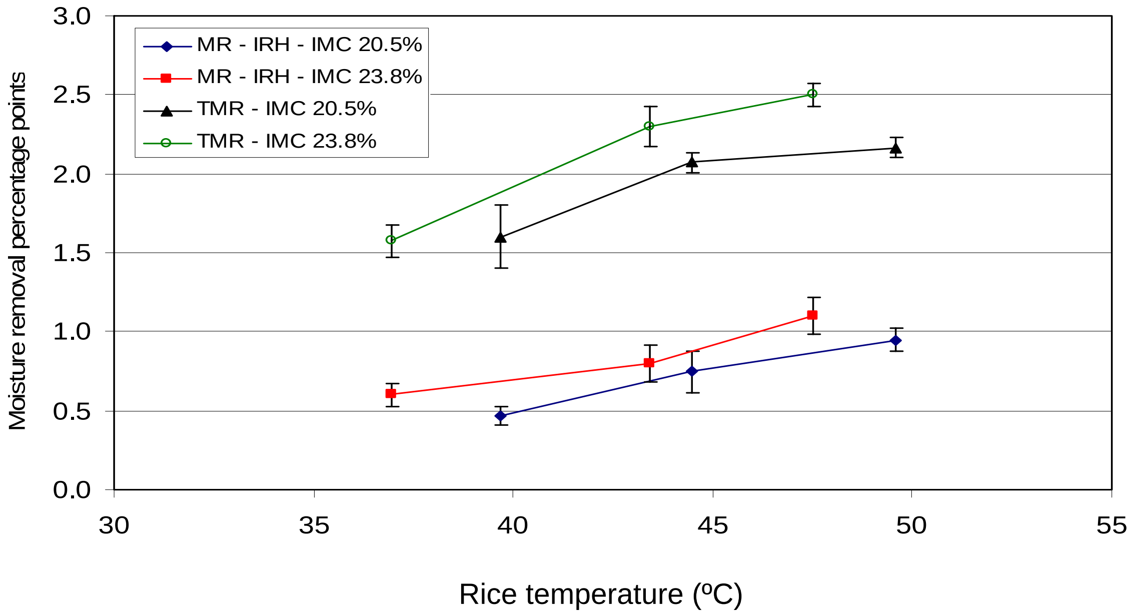
(ML – Moisture removal, IRH – infrared heating, TMR – total moisture removal)



(a)



(b)



(c)

Figure 3. Moisture removal of rice with initial MC of 20.5 % and 23.8% during infrared heating and after tempering treatment with drying bed thicknesses of single-layer (a), 5 mm (b), and 10 mm (c) under radiation intensity of 4685 W/m^2

(ML – Moisture removal, IRH – infrared heating, TMR – total moisture removal)

The rice moisture removal during infrared heating increased with the increased heating time and radiation intensity under a specific drying bed thickness and initial moisture content. The moisture removal increase resulted from increased rice temperature due to more energy being absorbed by the rice kernels with longer heating time and higher radiation intensity and caused more water evaporation compared to shorter heating time and low radiation intensity. When rice samples with different thicknesses were heated to a similar temperature, the moisture removal during heating was similar, indicating the thickness was not a limiting factor for the moisture removal. The MC removal depended on the rice temperature. For example, when the rice samples with initial moisture content of 20.5% were heated under radiation intensity of 5348 W/m^2 to 61.0, 60.2 and 61.2 ºC for drying bed thicknesses of single-layer, 5 mm and 10 mm, the corresponding moisture removals during infrared heating were 1.3, 1.4 and 1.3 percentage points, respectively. The corresponding total moisture removals, after tempering treatments, were 2.7, 2.6 and 2.5 percentage points. The same trend was noticed under low radiation intensity heating. When the rice samples with initial moisture content of 20.5% were heated under radiation intensity of 4685 W/m^2 to 48.8, 48.3 and 49.6 ºC for drying bed thicknesses of single-layer, 5 mm and 10mm, the corresponding moisture removals during infrared heating were 0.7, 0.7 and 0.8 percentage points, respectively. The corresponding total moisture removals, after tempering treatments, were 2.0, 2.2 and 2.2 percentage points.

The rice with high original moisture had more moisture removal than the one with low moisture, especially at the high temperature range. For example, when the rice samples with IMC of 20.5 % were heated under radiation intensity of 5348 W/m^2 to 60 ±1 ºC the moisture removal during infrared heating was 1.3, 1.4 and 1.3 percentage points for drying bed thicknesses of single-layer 5 mm and 10 mm, respectively. The corresponding total moisture removals were, after tempering treatments, were 2.7, 2.6 and 2.5 percentage points. When the rice samples with IMC of 23.8 % were heated under radiation intensity of 5348 W/m^2 to 60 ±1 ºC the moisture removals during infrared heating were 1.5, 1.6 and 1.5 percentage points for drying bed thicknesses of single-layer 5 mm and 10 mm, respectively. The corresponding total moisture removals were, after tempering treatments, were 3.7, 4.2 and 3.6 percentage points.

The results indicated that high drying rate was achieved during infrared heating with different drying bed thicknesses. For example, the drying rates of rice samples with initial moisture of 20.5 % were 1.3, 0.9 and 0.7 percentage point per minute each drying pass for drying bed thickness of single-layer, 5 mm, and 10 mm and heating time of 60 s. The drying rates of rice samples with initial moisture of 23.8 % were 1.5, 1.1 and 0.8 percentage point per minute each drying pass for drying bed thickness of single-layer, 5 mm, and 10 mm and heating time of 60 s. Therefore, it is important to notice that the high drying rate was achieved by using infrared heating alone even without counting the moisture removal during tempering and cooling compared to current commercial, conventional heated air drying of 0.1 to 0.2 percentage points per minute, due to the low heated air temperature used (Kunze and Calderwood, 1985).

Milled Rice Quality

In general, for both the rice samples with initial moisture contents of 20.5% and 23.8%, high TRY and HRY were achieved for drying bed thicknesses of single-layer, 5 mm and 10 mm by heating the rice samples to about 60 ºC compared to the controls (Figs. 4, 5, 6 and 7). On average, the TRYs of the rice samples with IMC of 20.5% heated to 61, 60.2 and 61.2 ºC and corresponding total moisture removals, 2.7, 2.6 and 2.5 percentage points were 69.26 %, 69.49 % and 69.20% for drying bed thicknesses of single-layer, and 5 mm and 10 mm, respectively (Fig 4). This meant that the TRY s of IR dried rough rice were 0.65, 0.88 and 0.59 percentage points higher than the controls (table 4).

The TRYs of the rice samples with initial moisture content of 23.8% heated to 60.6, 59.1 and 60.3 ºC and corresponding total moisture removal, 3.7, 4.2 and 3.6 percentage points were 68.98 %, 69.33 % and 68.96% (Fig 5) for drying bed thicknesses of single-layer, and 5 mm and 10 mm, respectively, which were 1.08, 1.43 and 1.06 percentage points higher than the controls (table 5). This means that high moisture removal and high TRY could be achieved during short time under drying bed thickness up to 10 mm.

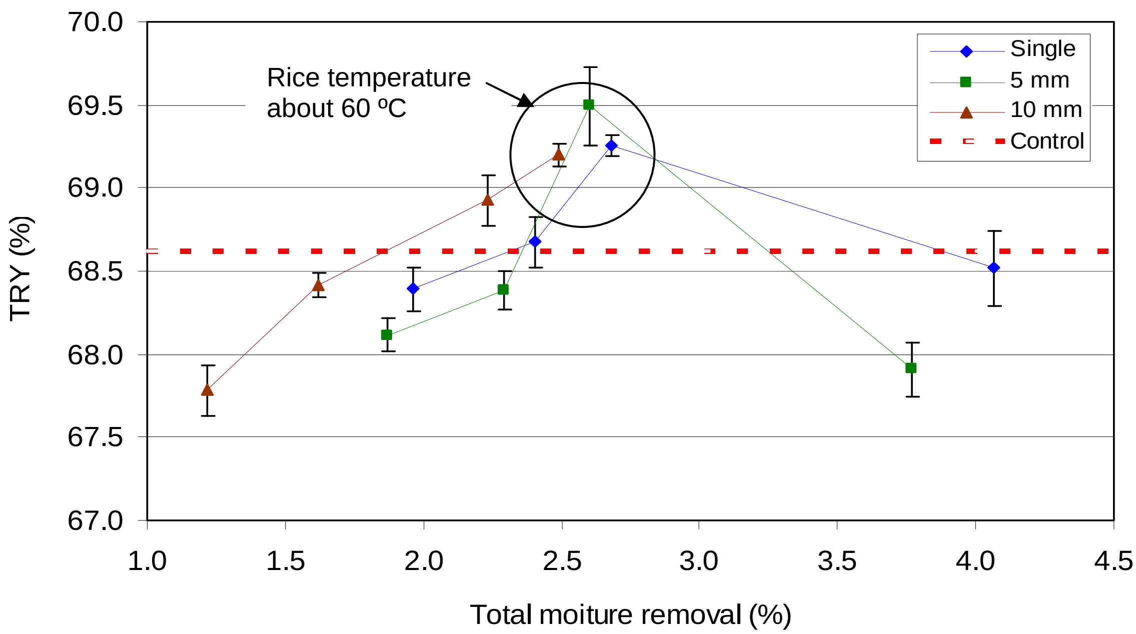


Figure 4. Total rice yields of rice with 20.5 % initial moisture content at different total moisture removals and drying bed thicknesses

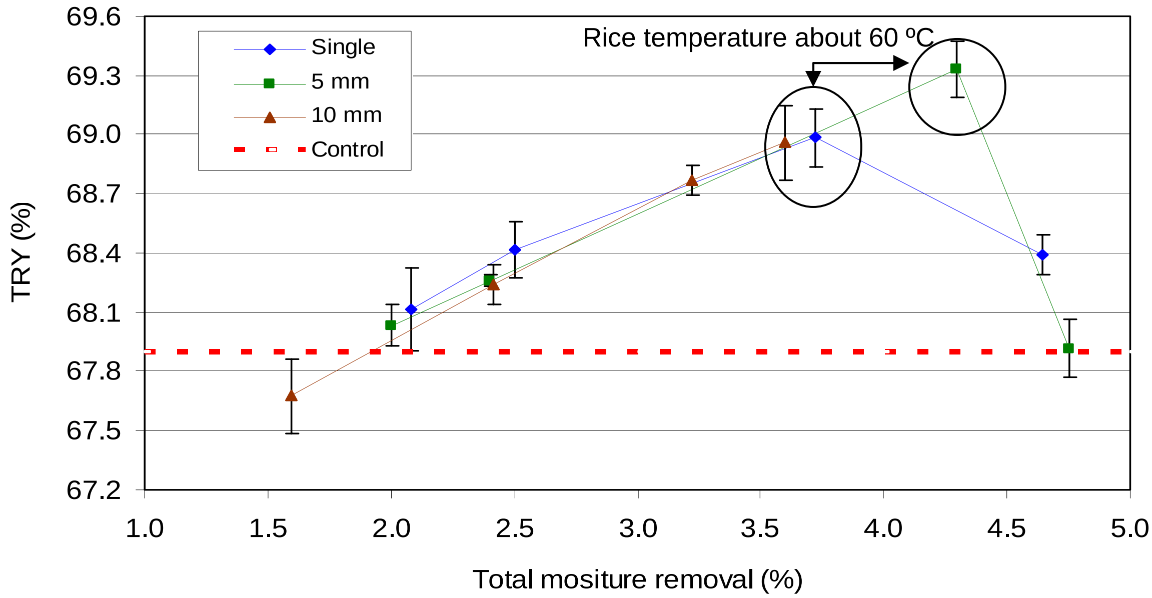


Figure 5. Total rice yields of rice with 23.8 % initial moisture content at different total moisture removals and drying bed thicknesses

Similar trends were also observed for the HRYs (Figs. 6 and 7).The low MC rice samples dried using IR with tempering and slow cooling had significantly higher HRY (1.52, 0.94 and 1.06 percentage points) than the control for rice samples heated to about 60 ºC at drying bed thicknesses of single-layer, and 5 mm and 10 mm, respectively, (table 4). For the rice samples with initial moisture of 23.8 %, heated to temperature about 60 °C, there was no significant difference between HRYs of rice dried at single-layer, 5 mm and 10 mm and control (table 5).

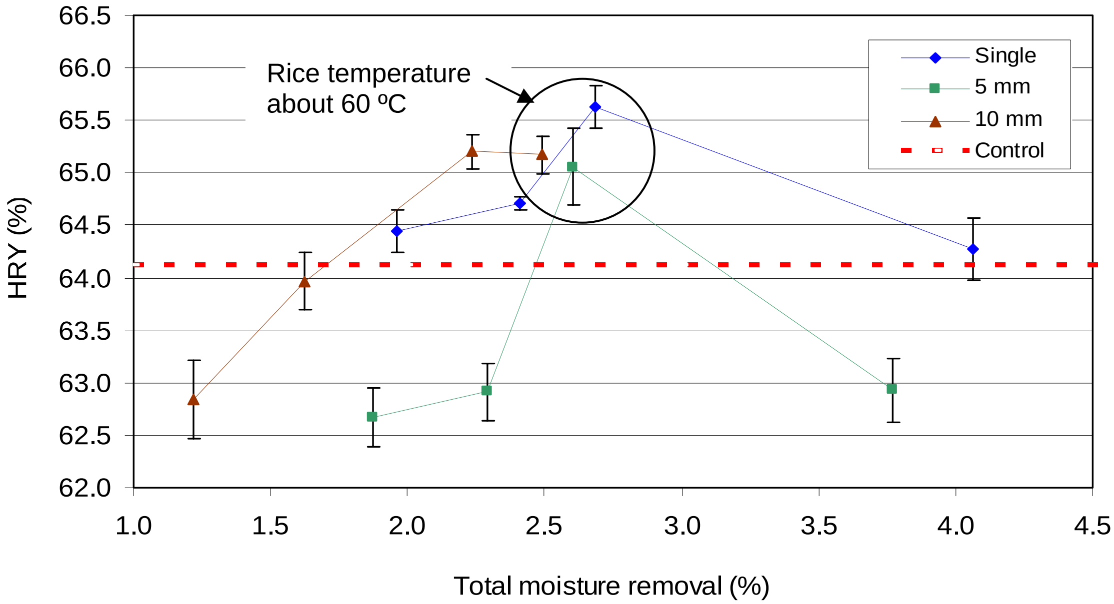


Figure 6. Head rice yields of rice with 20.5 % initial moisture content at different total moisture removals and drying bed thicknesses

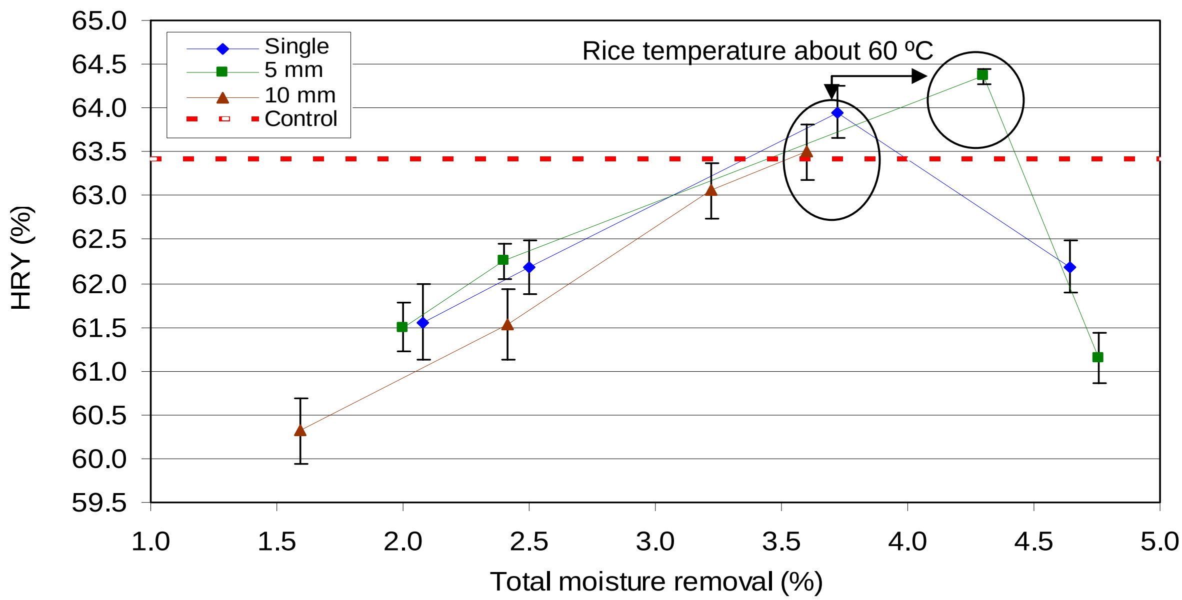


Figure 7. Head rice yields of rice with 23.8 % initial moisture content at different total moisture removals and drying bed thicknesses

Table 4. Quality of milled rice under different drying conditions with initial moisture content of 20.5 %.

Heating time (s)	Rice temperature (ºC)	Total moisture removal (%)	DBT and control [a]	Milled rice quality [b]		
				TRY	HRY	WI
			Control	68.61 a	64.11 a	41.90 a
15	42.6	2.0	Single-layer	68.39 ab	64.45 a	41.50 a
30	40.6	1.9	5 mm	68.11 bc	62.67 b	41.80 a
30	37.0	1.2	10 mm	67.78 cd	62.84 b	41.60 a
			Control	68.61 a	64.11 a	41.90 a
40	54.5	2.4	Single-layer	68.68 a	64.71 b	41.67 a
60	53.4	2.3	5 mm	68.38 a	62.91 c	41.80 a
60	46.2	1.6	10 mm	68.42 a	63.97 a	41.60 a
			Control	68.61 a	64.11 a	41.90 a
60	61.0	2.7	Single-layer	69.26 b	65.63 b	41.60 a
90	60.2	2.6	5 mm	69.49 bc	65.05 b	42.06 a
90	53.4	2.2	10 mm	68.82 ab	65.40 b	41.60 a
			Control	68.61 a	64.11 a	41.90 a
90	69.1	4.1	Single-layer	68.51 a	63.52 a	41.80 a
120	71.4	3.8	5 mm	67.91 b	62.77 b	42.00 a
120	61.2	2.5	10 mm	69.20 c	65.17 c	41.70 a

[a] DBT = drying bed thickness, Control = ambient air drying

[b] TRY = total rice yield, HRY = head rice yield, and WI = whiteness index. Values from the control, single-layer, 5 mm and 10 mm in each category followed by different letters are significantly different at $P < 0.05$.

Table 5. Quality of milled rice under different drying conditions with initial moisture content of 23.8 %.

Heating time (s)	Rice temperature (ºC)	Total moisture removal (%)	DBT and control [a]	Milled rice quality [b]		
				TRY	HRY	WI
			Control	67.90 a	63.40 a	41.80 a
15	42.4	2.1	Single-layer	68.12 a	61.55 b	41.50 a
30	39.7	2.0	5 mm	68.03 a	61.50 b	41.50 a
30	35.9	1.6	10 mm	67.70 a	60.32 c	41.50 a
			Control	67.90 a	63.40 a	41.80 a
40	53.8	2.5	Single-layer	68.42 b	62.18 b	41.40 a
60	50.6	2.4	5 mm	68.26 b	62.25 b	41.80 a
60	48.4	2.4	10 mm	68.24 b	61.53 b	41.50 a
			Control	67.90 a	63.40 ad	41.80 a
60	60.6	3.7	Single-layer	68.98 bc	63.95 abc	41.60 a
90	59.1	4.2	5 mm	69.33 b	64.36 c	41.70 a
90	52.3	3.2	10 mm	68.80 c	63.06 d	41.60 a
			Control	67.90 a	63.40 a	41.80 a
90	67.5	4.6	Single-layer	68.39 b	62.19 b	41.80 a
120	70.3	4.8	5 mm	67.92 a	60.85 c	41.80 a
120	60.3	3.6	10 mm	68.96 c	63.30 a	41.70 a

[a] DBT = drying bed thickness, Control = ambient air drying

[b] TRY = total rice yield, HRY = head rice yield, and WI = whiteness index. Values from the control, single-layer, 5 mm and 10 mm in each category followed by different letters are significantly different at $P < 0.05$.

When the results of the WI of milled rice were examined, it can be seen that there is no significant difference between the IR dried rice under different drying bed thicknesses and the control (tables 4 and 5). For all the rice samples dried under different drying bed thicknesses, heating times and radiation intensities, the WI values were more than 41.5 units .However, it seems that there is the trend that WI increased with the increase of the rice drying temperature for the rice samples with IMC of 20.5 and 23.8%.This could be due to the difference in the hardness of rice with different treatments and/or the contribution of broken kernels to the color, which need to be further studied.

Based on the milling quality results, it can be concluded that high moisture removal and milling quality could be achieved by heating the rice samples to about 60 ºC followed by tempering and slow cooling, the reason that the high temperature of IR heating did not damage the rice quality could be due to the relative uniform heating in the rice kernel resulting from the IR penetration, which had less moisture gradient compared to conventional heated air drying. The results indicate rice milling quality may not be compromised with a relatively large amount of moisture removal in a single drying pass with high drying rate if the rice can be heated quickly and uniformly for minimizing the moisture gradient. When a large amount of moisture is removed during IR heating, tempering is very important to reestablish the moisture equilibrium in rice kernels. Moreover, based on the glass transition hypothesis, the temperature and moisture at the rice surface were lowered first and starch reached glassy state during cooling. At the same time the center temperature and moisture of rice kernel were still relatively high and starch was remained at rubbery state. The differences in thermomechanical properties of starch at different stages would generate stress and fissure resulting in breakage in milling and lowered rice milling quality. Therefore, controlled slow cooling will be very important for high temperature rice drying. Since the slow cooling effectively preserved rice quality, controlled slow cooling could be accomplished by low rates of air flow through a bin of rice to cause cooling.

Conclusions

The research showed that the high rice drying temperatures can be achieved with a relatively short heating time by using catalytic IR emitter with different drying bed thicknesses. The moisture removal during heating increased with an increase in rice temperature. It took only 60, 90 and 120 s to achieved about 60°C rice temperature and removed 1.3, 1.4 and 1.3 and 1.5, 1.6 and 1.5 percentage points during heating alone for the low and high MC rice, and drying bed thicknesses, single-layer, 5 mm and 10 mm, respectively. The corresponding total moisture removals, after tempering and slow cooling treatments, were 2.7, 2.6 and 2.5 and 3.7, 4.2 and 3.6 percentage points.

The tempering process after the rapid IR heating and moisture removal is essential to achieve high rice milling quality and improve the amount of moisture removal during cooling. The slow cooling following the tempering treatment can be used to remove a significant amount of moisture and achieve good rice quality without additional energy input.

The recommended conditions for drying of freshly harvested rice are 60°C rice temperature followed by tempering and slow cooling at drying bed thickness up to 10 mm.

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